

Radiative Processes in Microquasars

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Abstract. Recent advances in the X-ray and soft γ -ray observations of accreting black holes and microquasars, in particular, are reviewed. The radiative processes responsible for the emission are discussed briefly. The hybrid thermal/nonthermal Comptonization model is shown to describe well the observed broad-band spectra. We also comments on alternative phenomenological and physical models that are used to describe the X/ γ -ray spectra of accreting black holes. Among those are the “standard” model (i.e. disk-blackbody plus a power-law), PEXRAV, bulk motion Comptonization, and synchrotron emission from the jet.

1. Introduction

Accreting black holes radiate in the two main spectral states which we refer to later as hard and soft (see Fig. 1). The hard state is characterized by a power-law-like spectrum which abruptly cuts off at ~ 100 keV. The energy output is dominated by the 100 keV photons [2]. Such a spectrum is interpreted as Comptonization by thermal electrons in the inner hot disk or active magnetic corona above the accretion disk (e.g. [3, 4, 5]). A weak MeV tail observed in Cyg X-1 is probably a signature of non-thermal electrons in the source [6, 7, 8].

In the soft state the emission is dominated by the black-body-like component peaking at a few keV with a power-law-like component above 30 keV extending up to 1 MeV or even higher [2, 8, 9, 10]. These spectra cannot be fitted with thermal Comptonization models and require the radiating electrons to have a significant non-thermal fraction [7, 11, 12].

2. Spectral Modeling

2.1. *Cygnus X-1*

A weak MeV tail observed in Cyg X-1 in its hard state already shows us that the emitting electrons cannot be purely thermal (see left panel of Fig. 2). An obvious generalization is to assume that there is a non-thermal tail in the electron distribution that is produced by some acceleration process (e.g. [6]). The soft state data (even below 1 MeV) could not be fitted at all with thermal models. Modeling of the spectral transitions with a generalized hybrid thermal/non-thermal model EQPAIR [7, 13] predicted a stronger power-law-like tail in the soft state extending up to 10 MeV. *CGRO*/COMPTEL observations confirmed the existence of this tail: the decrease of the hard X-ray luminosity was accompanied by the *increase* of the soft γ -ray luminosity [8]. In the context of the hybrid Comptonization model, the power-law is a result of single Compton scattering off non-thermal

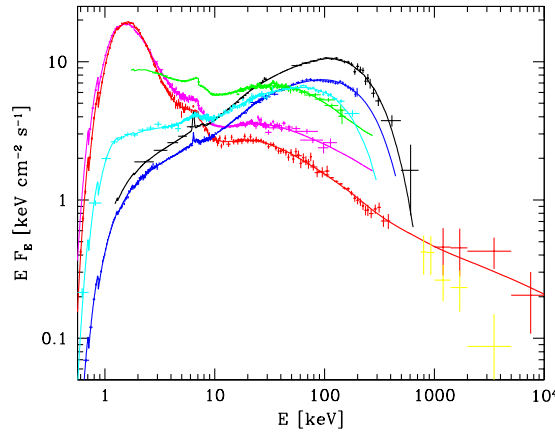


Figure 1. A collection of broad-band spectra of Cyg X-1. The solid curves give the best-fit Comptonization models (thermal in the hard state, and hybrid, thermal-nonthermal in the other states). From [1].

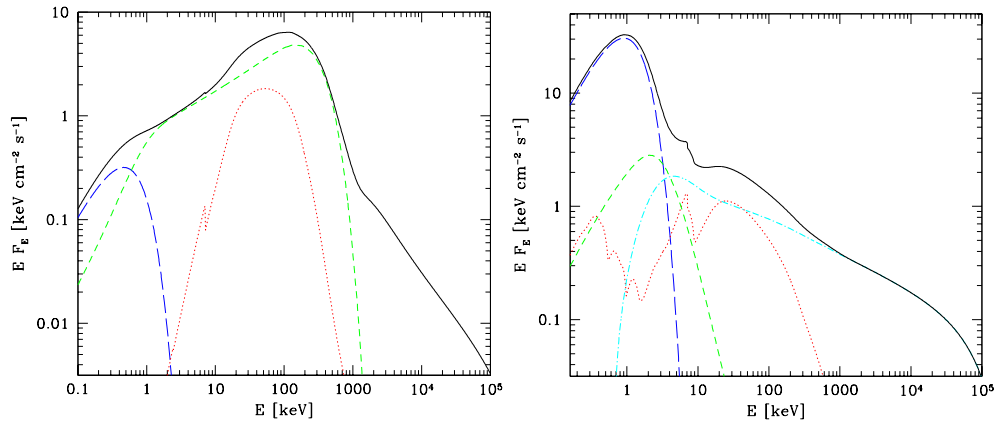


Figure 2. Left: Components of the EQPAIR fit to the hard state *CGRO* data of Cyg X-1. The long dashes, short dashes, and dots correspond to the unscattered blackbody, scattering by thermal electrons, and Compton reflection, respectively. The solid curve is the total spectrum. Scattering by the nonthermal electrons accounts for the high-energy tail above the thermal-Compton spectrum given by the short dashes, starting at ~ 1 MeV. Right: Components of the EQPAIR fit to the *BeppoSAX-CGRO* data for the soft state of Cyg X-1. The curves have the same meaning as in the left panel. The dots/dashes correspond to the scattering by nonthermal electrons. All spectra are intrinsic, i.e., corrected for absorption. From [8].

population of electrons (see right panel in Fig. 2). A cutoff at about 10 MeV (depending on the compactness of the source) should appear in the spectrum due to the absorption of the γ -rays by softer photons resulting in pair production.

2.2. *GRS 1915+105*

In spite of the fact that microquasar *GRS 1915+105* show dramatic variability pattern, almost all its hard X-ray spectra are remarkably similar. During eight (out of nine) observations with the *CGRO/OSSE* the source showed a simple power-law-like spectrum in the 50–500 keV band with photon index $\Gamma \approx 3$ [12]. Only in one occasion (when the X-ray flux was very high), the hard X-ray spec-

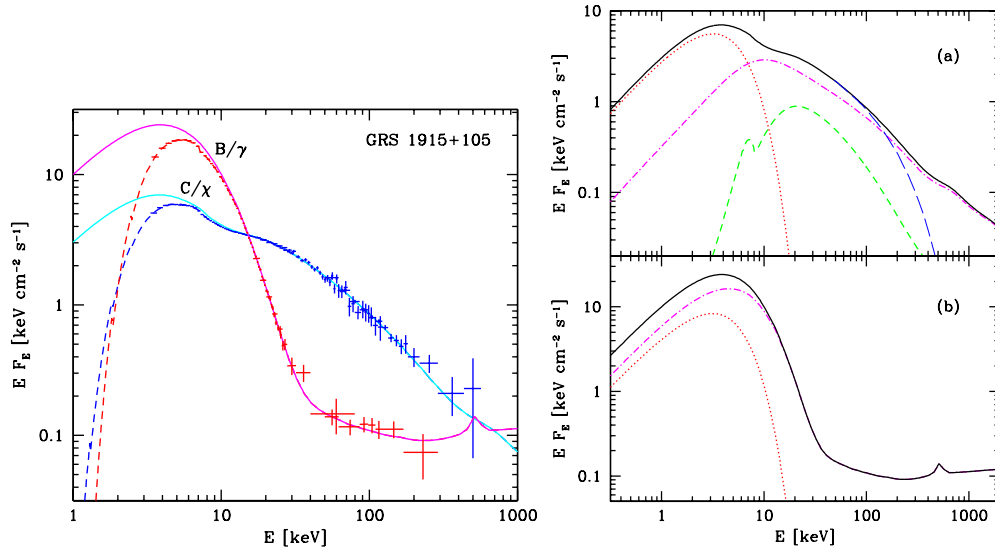


Figure 3. Left: Fits to simultaneous *RXTE*-*OSSE* spectra of GRS 1915+105 from VP 619 (1997 May 14–20) and VP 813 (1999 April 21–27) with the hybrid Comptonization model *EQPAIR*. The dashed and solid curves show the models of the observed spectra and the unabsorbed spectra, respectively.

Right: (a) Components of the fit to the VP 619 data. All spectra are intrinsic, i.e., corrected for absorption. The dotted, dot-dashed and dashed curves give the unscattered blackbody component, the scattered spectrum, and the component due to Compton reflection and Fe $K\alpha$ fluorescence, respectively. The solid curve is the total spectrum. The thin long-dashed curve shows the best-fit thermal Comptonization model, which lies much below the data above 100 keV. (b) The total model spectrum and the corresponding two components for the VP 813 data. The cutoff at ~ 10 MeV is due to photon-photon pair production absorption. From [12].

trum was much harder $\Gamma \approx 2.3$ and the flux was low. We note here that in all observations the source has a much softer spectrum than the normal hard state of Cyg X-1, i.e. it was always in the soft state. There is no signature of the high-energy cutoff in the data. The *EQPAIR* model gives a good description of the data (see Fig. 3) indicating that about 10-20% of the total power goes to accelerate non-thermal electrons. The C/ χ -state [14] differs, however, from the B/ γ -state in that the 20-200 keV tail is produced by thermal Comptonization in the former and by non-thermal Compton scattering in the later.

3. Old and New Alternatives

3.1. The “standard” model

The black body looking soft component is associated with the optically thick accretion disk by most of the researchers. The broad-band spectra are often fitted by the “standard” model consisting of a disk-blackbody (soft component) and a power-law (hard). There are numerous problems with such modeling. First, a black body is a bad representation of the spectrum expected from the accretion disk (e.g. [15]). Real data also show that the soft bumps in the Cyg X-1 soft state [11] and GRS 1915+105 [12] cannot be fitted by a black body (or multi-color disk). Thermal Comptonization of a blackbody is a much better description of these spectra. Second, a power-law, even exponentially folded, is a very bad

representation of the Comptonization spectra. At the lower end, Comptonization spectrum cuts off below the seed photon energy while a power-law has no break there. The normalization of the blackbody thus can be underestimated by a large factor (see e.g. [16]). The conclusions (e.g. variations of the inner disk radius) resulting from fitting the data with this “standard” model thus should be taken with a grain of salt.

At the higher end, the (thermal) Comptonization spectrum has a much sharper cutoff than an exponentially folded power-law. This difference in the spectral shape is important when we model the broad-band spectra from accreting black holes with the later model adding a Compton reflection component (model PEXRAV [17] from XSPEC) since the amplitude of the reflection component strongly depends on the assumed shape of the underlying continuum. Thus, we would advise not to use PEXRAV when modeling Comptonization spectra close to the black body or to the high energy cutoff.

3.2. *X-rays from the jet?*

Recently, a very interesting correlation between radio and X-ray fluxes has been discovered [18, 19, 20]. There are two possible origins of this correlation. One is that the level of X-ray emission is related to the rate of ejection of radio-emitting clouds, forming a compact jet (e.g., [19, 21]). Another is that the X-ray emission of black hole binaries is dominated by the synchrotron emission of the jet [22, 23, 24].

We note here there are many strong arguments against the second interpretation. The broad-band X/ γ -ray spectra of black hole binaries in the hard state are very well modeled by thermal Comptonization and Compton reflection (e.g., [25, 26, 27, 28]). The presence of reflection implies that the X-ray emission is not strongly beamed away from the disc. The thermal-Compton origin of the primary X-ray emission is strongly supported by a remarkable uniformity of the both energy and shape of the high-energy cutoffs of black hole binaries in the hard state observed by OSSE [10]. This cutoff is naturally accounted for by thermodynamic properties of thermal Comptonization as well as e^\pm pair production (e.g., [5]), as it corresponds to the transition to relativistic temperatures. At higher temperatures, cooling becomes extremely efficient and copious pair production starts. This reduces the energy available per particle leading to the temperature decrease. On the other hand, $m_e c^2$ plays no particular role for non-thermal synchrotron emission (cf. variable cutoff energy during flares in blazars). Thus, accounting for the observed cutoff energies requires fine-tuning of product of the magnetic field strength and the square of the maximum electron energy in the non-thermal synchrotron model. In addition, the jet model has problems reproducing the actual shape of the cutoff. For example, the synchrotron model of the hard state of Cyg X-1 (see fig. 3a in [23]) when matched to the 100 keV flux overestimates the 1 MeV flux (see [8]) by a factor of 8.

An additional evidence against a substantial part of X-rays being non-thermal synchrotron is provided by spectral variability. In the case of Cyg X-1, the ASM/BATSE data show spectral pivoting around ~ 40 – 50 keV (see [1] and Fig. 4). The characteristic variations of the power-law slope $\Delta\Gamma$ from those data is ~ 0.2 – 0.3 . This power-law spectral variability extended to 15 GHz would imply a huge variability of the radio flux, by several orders of magnitude. However, the range of the variability of the 15 GHz flux correlated with the ASM flux is by a factor of several, basically the same as the range of the variability of the ASM flux itself [20]. If both radio and X-rays were due to non-thermal synchrotron

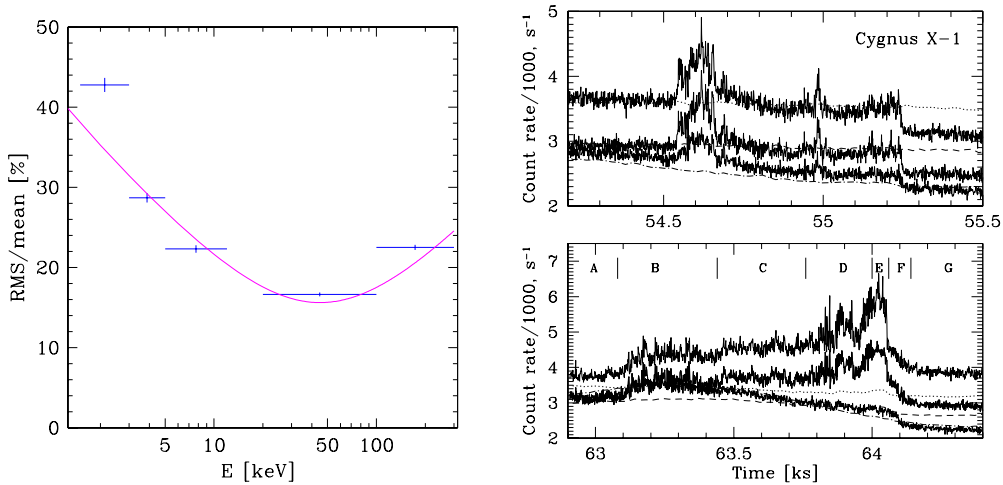


Figure 4. Left: The rms variability in the hard state of Cyg X-1 in one-day averaged data from the *RXTE*/ASM and *CGRO*/BATSE [1]. The model curve corresponds to a power-law pivoting with $\Delta\Gamma \simeq 0.2$ around the energy which has a Gaussian distribution around 45 keV (see [29] for details).

Right: Count rate during the two outbursts of Cyg X-1 on 1999 April 21 in the BATSE large area detectors energy channels 1–3 (corresponding to approximately 20–50 keV, 50–100 keV, 100–300 keV). Count rates are higher in softer channels. The count rate is summed over two detectors closest to the line of sight to Cyg X-1. Dashes, dots, and dash/dots show the background in channels 1, 2, 3, as seen by two detectors looking away from Cyg X-1. From [32].

emission, their observed variability pattern should yield the rms in X-rays virtually independent of energy. This is clearly in strong disagreement with the data shown in Fig. 4, and, in particular, with the ASM 1.5–3 keV flux being strongly anticorrelated with the 100–300 keV flux from BATSE [1].

The amplitude of Compton reflection and the iron line imply that dense and rather cold material occupies a solid angle $\sim \pi$ as viewed from the X-ray source. Smearing of these components and the observed correlations with the spectral slope [29, 30, 31] clearly identifies the reflector with the accretion disk and implies the origin of the continuum emission within 30–100 gravitational radii from the black hole which would also be consistent with rapid X-ray variability.

All these arguments strongly support the interpretation of the correlated radio emission as being due to ejection of clouds from the X-ray source which could be similar to coronal mass ejections (CME) observed at the Sun. The recently discovered strong X/ γ -rays flares from Cyg X-1 [32, 33] could be the extremes of such an activity. The right panel in Fig. 4 shows the flaring activity of Cyg X-1 in April 1999. The episode D–E shows strong flare in the 20–100 keV band with a weaker activity above 100 keV and no detectable signal above 300 keV. This indicates that there exist at least two independent spectral components (see [32]): one could be related to the inner hot disk or the magnetized corona, while another to the base of the jet.

3.3. Bulk motion Comptonization

The power-law like spectra of black holes in the soft state were interpreted as resulting from bulk motion Comptonization in the converging flow [34, 35, 36].

The specific feature of that model is a cutoff at $\sim 100\text{--}200$ keV. (We note here that the XSPEC version of the model BMC has no cutoff built in.) The data show no signatures of the cutoff at least up to 500 keV in GRS 1915+105 [12] and up to 10 MeV in Cyg X-1 [8]. This supports their non-thermal origin and strongly rules out a significant contribution from the bulk motion Comptonization. (See further discussion in [2, 12].)

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